International Journal of Phytoremediation, 6(3):239–252 (2004)

ISSN: 1522-6514
DOI: 10.1080/16226510490496438

Taylor & Francis
Taylor & Francis Group

Determination of the Relative Uptake of Ground vs. Surface Water by *Populus deltoides* During Phytoremediation

Barton D. Clinton,[1,*] James M. Vose,[1] Don A. Vroblesky,[2] and Gregory J. Harvey[3]

[1]USDA Forest Service Southern Research Station, Otto, North Carolina, USA; [2]U.S. Geological Survey, Columbia, South Carolina, USA; [3]U.S. Air Force, Wright Patterson Air Force Base, Ohio, USA

Address correspondence to Barton D. Clinton, USDA Forest Service Southern Research Station, Coweeta Hydrologic Laboratory, 3160 Coweeta Lab Road, Otto, NC 28763, USA. E-mail: bclinton@fs.fed.us

ABSTRACT

The use of plants to remediate polluted groundwater is becoming an attractive alternative to more expensive traditional techniques. In order to adequately assess the effectiveness of the phytoremediation treatment, a clear understanding of water-use habits by the selected plant species is essential. We examined the relative uptake of surface water (i.e., precipitation) vs. groundwater by mature *Populus deltoides* by applying irrigation water at a rate equivalent to a 5-cm rain event. We used stable isotopes of hydrogen (D) and oxygen (^{18}O) to identify groundwater and surface water (irrigation water) in the xylem sap water. Pretreatment isotopic ratios of both deuterium and ^{18}O, ranked from heaviest to lightest, were irrigation water > groundwater > xylem sap. The discrepancy in preirrigation isotopic signatures between groundwater and xylem sap suggests that in the absence of a surface source of water (i.e., between rain events) there is an unknown amount of water being extracted from sources other than groundwater (i.e., soil surface water). We examined changes in volumetric soil water content (%), total hourly sapflux rates, and trichloroethene (TCE) concentrations. Following the irrigation treatment, volumetric soil water increased by 86% and sapflux increased by as much as 61%. Isotopic signatures of the xylem sap became substantially heavier following irrigation, suggesting that the applied irrigation water was quickly taken up by the plants. TCE concentrations in the xylem sap were diluted by an average of 21% following irrigation; however, dilution was low relative to the increase in sapflux. Our results show that water use by *Populus deltoides* is variable. Hence, studies addressing phytoremediation effectiveness must account for the relative proportion of surface vs. groundwater uptake.

KEY WORDS: trichloroehtene, stable isotopes, xylem sapflux.

INTRODUCTION

Plants are being used to remediate polluted soil and groundwater (Flathman and Lanza, 1998). Although native vegetation growing over polluted substrates may have a measurable impact on pollutants, using plant species known for high rates of transpiration and their ability to metabolize, store, and/or mineralize specific pollutants may be a more attractive alternative. A full understanding of the water-use patterns of plant species being considered is critical to the successful use of phytoremediation (Vose *et al.*, 2000, 2003). In order to accurately estimate the amount of pollutant extracted from groundwater, it is essential to know the relative contribution of groundwater to plant transpirational water use. Phreatophytes are plant species whose deep roots draw on shallow groundwater tables (Kozlowski *et al.*, 1991). Obligate phreatophytes are those who rely solely on groundwater, while facultative phreatophytes preferentially switch from groundwater to other sources, depending on availability and transpirational demand, among other factors.

Generally, water uptake by roots occurs in soil with the highest water potential (least negative pressures), which corresponds to the wettest soil layers and/or areas with the largest pore sizes (Kozlowski *et al.*, 1991). Dimorphic root systems (roots generally distributed evenly between shallow and deep soil layers) can take up water from different soil layers. Water from these different layers can have a unique chemical composition or signature, such as the relative proportion of stables isotopes of H (D) and O (δ^{18}O). Because soil water is transpired through stem sapwood, stem-water isotopic signatures may provide an indicator of the location of water uptake within the rooting zone. The utility of using stable isotopes of water as a tool for understanding water use by plants is based on the fundamental observation that there is no isotopic fractionation of either hydrogen or oxygen isotopes during water uptake by roots (Allison *et al.*, 1984; Dawson and Ehleringer, 1991; Wershaw *et al.*, 1966; White *et al.*, 1985). The isotopic composition in the xylem sap after uptake remains unaltered from that in the soil water until it reaches tissues undergoing water loss (i.e., leaves or unsuberized stems), where evaporative enrichment of hydrogen and oxygen isotopes takes place. If the hydrogen or oxygen isotopic composition of xylem sap is analyzed before it has been exposed to evaporative processes, the isotopic composition is an integrated measure of overall water uptake, reflecting the various zones and depths from which the plant is currently extracting water (Ehleringer and Dawson, 1991).

Much is known about the water-use habits of *Populus* spp. (Heilman *et al.*, 1996; Pallardy and Kozlowski, 1981; Vose *et al.*, 2000). To our knowledge, no attempt has been made to examine sources of water uptake at sites where plants are specifically used for contaminant remediation or hydraulic control. We studied the relative uptake of surface soil water (i.e., recent precipitation) vs. groundwater by eastern cottonwood [*Populus deltoides* (Bartr.)] to determine if uptake from unsaturated soil reduced the effectiveness of eastern cottonwood during phytoremediation of a groundwater pollutant. We used stable isotopes of hydrogen (as δD) and oxygen (as δ^{18}O) to identify groundwater and surface water in the xylem sap water. Moreover, artificial irrigation experiments were performed to test the hypothesis that, during irrigation, *P. deltoides* would rely predominantly on irrigation water, but would use a mixture of water after irrigation ceased.

METHODS

Site Description

The study site is located in north-central Texas in Tarrant County, about 15 km west of Fort Worth, and is in the Grand Prairie section of the Central Lowland Physiographic Region (Bailey and Hogg, 1986) (Figure 1). The topography in the region is flat to gently rolling and, at the study site, is generally flat but gently sloping toward Farmer's Branch Creek. The climate is characterized as subhumid, with mild winters and hot humid summers. Average annual precipitation is 80 cm, with most rainfall occurring between May and October. Average annual temperature is 18.6°C.

The study site is located on the Naval Air Station (formerly Carswell Air Force Base), which adjoins U.S. Air Force Plant 4 (AFP4) on the west and the Carswell Golf Club on the south. Manufacturing processes at AFP4 produced an estimated 2.5–2.7 tons of waste per year. These wastes included solvents, oils, fuels, paint residues, and

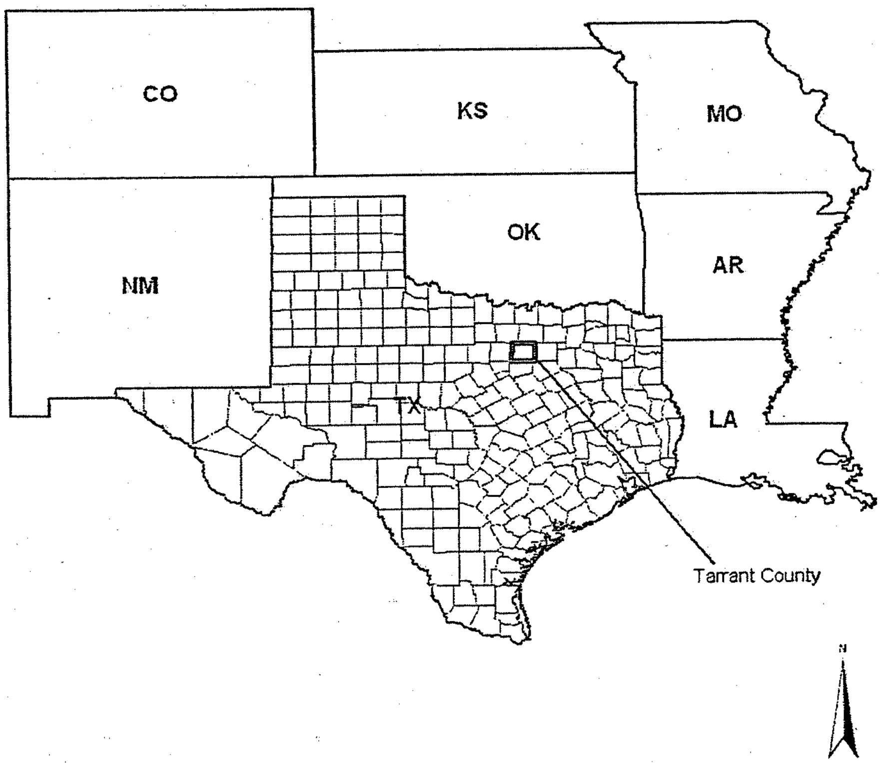

FIGURE 1. Location map for study site. Tarrant County, TX, is approximately 15 km west of the Dallas/Fort Worth metropolitan area.

other chemicals (Vose *et al.*, 2000). Historically, wastes were disposed of on-site in landfills or were burned in fire-training exercises. Currently, waste oils and solvents are disposed of by contractors and chemical wastes are treated on-site before being discharged into the municipal treatment facility (Vose *et al.*, 2000).

Surface soils (0–200 cm) at the site are characterized as clayey to silty clay at the surface, to clay loam in the deeper horizons (USDA Soil Survey, 1981). The uppermost hydrogeologic unit at APF4 is a terrace alluvial aquifer (TAA) consisting of silt, clay, sand, gravel, and fossiliferous limestone (Vose *et al.*, 2000). Groundwater occurred at depths of 2.0–3.4 m from the soil surface. Recharge of TAA is primarily by precipitation, but the TAA also receives inputs from leaking sewer lines, water mains, and runoff from a nearby tarmac. The presence of trichloroethene (TCE) was detected in the TAA in 1985. Further analyses indicated the presence of cis-1, 2-dichloroethene (DCE), as well. Maximum concentrations of the TCE and DCE were 960 and 131 $\mu g\ L^{-1}$, respectively (for further site description, see Vose *et al.*, 2000 and Eberts *et al.*, 2003).

Sapflow Measurements

Sapflow techniques were used to estimate individual tree transpiration rates (Hinckley *et al.*, 1994; Martin *et al.*, 1997). We selected two mature open-grown eastern cottonwood trees growing over the delineated plumes of TCE and DCE in groundwater. Sapflow probes (Granier thermal dissipation approach; Granier, 1985, 1987) were installed at five levels up the stem, beginning approximately 25 cm above the ground and continuing at 1-m intervals. Average diameters taken at each of the five levels were 92.5 and 74.8 cm. Six sapflow probes were installed at each level and sapflow estimates from each probe were averaged to obtain a mean sapflow estimate for each tree. Sapflow was measured continuously for 4 d (July 18–22, 2000). At the end of the measurement period, sapwood thickness was estimated by measuring sapwood on tree cores taken near each probe and averaged at the tree level. Sapflow velocity (cm h^{-1}) was converted to sapflux ($cm^3\ h^{-1}$) based on the cross-sectional area of sapwood at each level and then converted to a mass basis (kg h^{-1}) and averaged at the tree level.

Irrigation Treatments

Irrigation water was applied around each tree at the rate of 1600 L h^{-1} (5-cm rainfall equivalent) during the morning on two consecutive days. Irrigation water was applied using drip hoses beginning at the base of the tree and extending to the edge of the tree crowns. We assumed that the existence of feeder roots beyond the edge of the tree crowns was not significant. Based on saturated hydraulic conductivity values typical of clayey or silty clay soils (Brady, 1974) and an average groundwater depth of 2.7 m, applied irrigation water did not reach groundwater during the course of the study. Volumetric soil water content (%) in the upper 20 cm of soil increased by 86% (46.7%–86.7%) following the first irrigation and, following a reduction in soil moisture by 6% between irrigation treatments, increased by an additional 13% (80.7%–91.0%) after the second irrigation (Figure 2). The irrigation water source was a City of Fort Worth reservoir.

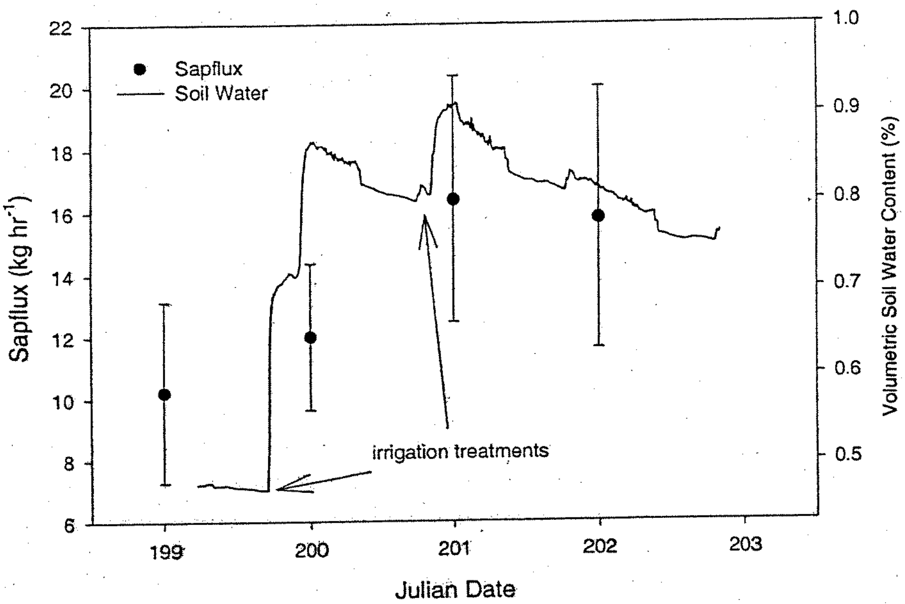

FIGURE 2. Changes in sapflux (kg hr^{-1}) and volumetric soil water content (%) during the study period. Individual observations in sapflux are means across levels ($n = 5$) and trees ($n = 2$). Error bars represent 1 standard error of the mean. Plot of soil water content represents the mean of eight measurement locations within the irrigated area.

Stable Isotope Composition

We collected 24 tree cores with an increment borer, 12 before and 12 after irrigation, from three levels along the main stem of each tree; i.e., two treatments (pre- and post-irrigation) × three levels × two cores per level × two trees, for isotopic signature determination (i.e., $\delta^{18}O$ and δD) of the xylem sap. We took groundwater samples from adjacent U.S. Geological Survey (USGS) test wells on site. Care was taken to minimize evaporative enrichment. Tree cores, groundwater samples, and irrigation water were extracted, handled, and stored in accordance with established protocols (Stable Isotope Ratio Facility for Environmental Research, 2001). Isotopic analyses were conducted at the Stable Isotope Ratio Facility for Environmental Research (SIRFER) in the Biology Department, University of Utah, Salt Lake City.

TCE Analyses

Tree cores (approx. 4 cm in length) were collected using an increment borer before, during, and after the irrigation treatment (for methodology see Vroblesky *et al.*, 1999). Cores were immediately removed from the increment borer and placed in 20-ml glass vials. Teflon[1]-coated septum caps were then crimped onto the vials. Ambient-air

[1]The use of trade or firm names in this publication is for reader information and does not imply endorsement by the U.S. Department of Agriculture of any product or service.

samples were collected by waving empty 20-ml glass vials in the air for several seconds and sealed with septum caps. The cores were allowed to equilibrate in the sealed vials at room temperature for 24–48 h. Head-space samples were collected from each vial by piercing the septated vial cap with a gas-tight syringe and withdrawing 100 μL (microliters) of vapor. Gas samples were packed in ice and transported to the USGS laboratory in Columbia, SC, for analysis of TCE by photo-ionization detection on a Photovac 10S Plus[1] gas chromatograph.

RESULTS AND DISCUSSION

Sapflux

Pre-irrigation sapflux rates, expressed on a sapwood-area basis, were slightly less than rates reported by others for this species. For example, rates reported by Vose *et al.* (2000) for small stems (<8-cm basal diameter) averaged close to 0.04 kg $cm^{-2}\,h^{-1}$ across the range of observed solar radiation and vapor pressure deficit (VPD). Similarly, Hinckley *et al.* (1994) reported sapflux rates for stems of *Populus* species 12-cm diameter at breast height (DBH) of approximately 0.02 kg $cm^{-2}\,h^{-1}$. We found a sapflux rate for mature stems >70-cm DBH of 0.016 kg $cm^{-2}\,h^{-1}$. Several factors could contribute to these differences, such as local site and climatic conditions, tree size, and the health and vigor of measured trees.

Sapflux rates increased by 11% following the first irrigation period to 61% after the second and remained elevated the day following the second irrigation treatment (Figure 2). Because transpiration is driven by climatic conditions as well as water availability, we plotted pre- and post-irrigation climatic driving variables (Figure 3) and compared them to transpiration response. As shown in Figure 3, climatic conditions during the study period did not vary significantly; hence, post-irrigation increases in sapflux rates were most likely driven by changes in water availability, not changes in climate variables, such as VPD, solar radiation, or temperature.

Volumetric soil water content (%) prior to irrigation was 47%. Vose *et al.* (2000) reported that soil moisture content for this site during the growing season (May–October) ranged from 27–80%, responding to periodic rainfall (inputs) and transpiration and drainage (outputs). However, matrix potentials for these soils have been shown to be high (J.M. Vose, unpublished data); hence, although water content appeared to be high (47% by volume), availability was likely low.

After irrigation, soil water content increased to almost 90%, representing fully saturated conditions in the root zone. The magnitude of the increase in transpiration after irrigation suggests a dimorphic root distribution and that recently applied irrigation water is easily taken up by roots from the saturated surface soils.

Isotopic Compositions

The isotopic compositions of the groundwater, irrigation water, and pre- and post-irrigation xylem sap, expressed as ratios of the heavy to light isotope, are shown in Table 1. All water sources had distinctly different isotopic ratios and the irrigation water was substantially more enriched in both ^{18}O and D relative to the groundwater. Groundwater isotopic ratios for this study were −22.0% for deuterium and −3.8% for ^{18}O. An independent analysis of groundwater isotopic ratios in 1998 (S. Jones,

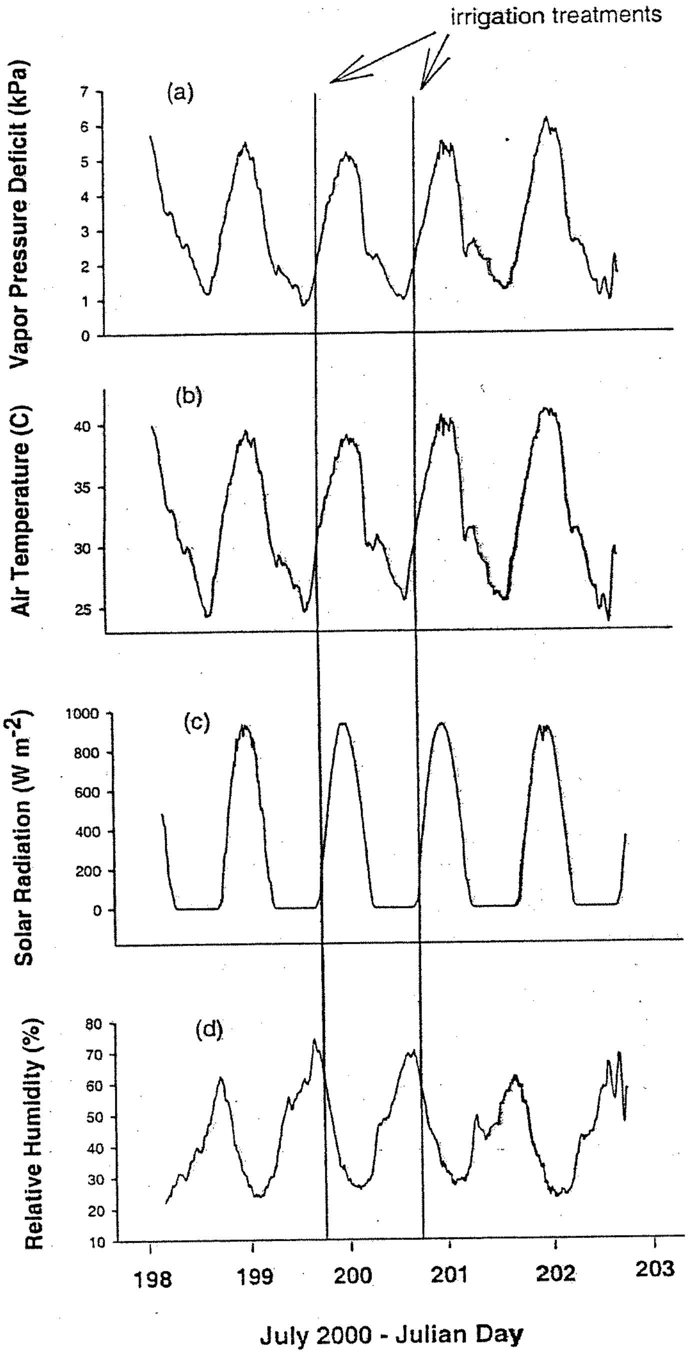

FIGURE 3. Variation in climate over the measurement period. Plots represent 15-min running averages for (a) vapor pressure deficit, (b) air temperature, (c) solar radiation, and (d) relative humidity. Julian days on the X-axis are positioned at mid-day.

TABLE 1. Values of $\delta^{18}O$ and δD (% V-SMOW) for groundwater, irrigation water, and pre- and post-irrigation xylem sap. Values in parentheses for xylem sap are standard errors ($N = 12$). $N = 2$ for groundwater and irrigation water.

Source	$\delta^{18}O$	δD
Groundwater	−3.8	−22.0
Irrigation water	0.9	8.0
Pre-irrigation xylem sap	−4.5 (0.13)	−39.5 (1.00)
Post-irrigation xylem sap	−3.6 (0.19)	−33.3 (0.97)

personal communication.[2]) from the same wells used in this study were −23.8% for deuterium and −4.3% for ^{18}O. Our isotope ratios for groundwater were only slightly heavier than this earlier analysis. One explanation for the more enriched irrigation water relative to groundwater would be that the source of the irrigation water was a large shallow reservoir where accelerated evaporative isotopic enrichment took place. Isotopic ratios for groundwater in "closed basins" are typically more enriched than the meteoric water that feeds them. The degree of enrichment likely varies with changes in inputs and evaporation (i.e., composition is likely season and rain-event dependent). For example, due to the "continental effect," δD in meteoric waters in north-central Texas ranges widely, from −50 to −120% (Ingraham, 1998), except during the monsoon season of the southwestern U.S., when δD is typically greater than −120%.

The difference toward the heavier isotope of hydrogen and oxygen following irrigation represents a shift in the isotopic signature in the xylem sap of about 16% for δD and 20% for $\delta^{18}O$, indicating a shift in water use following irrigation (Figure 4). Pre-irrigation isotopic ratios of xylem sap indicate that *P. deltoides* were using a mixture of groundwater and available soil water that was more negative than groundwater. Because we did measure the isotopic signature of soil water, we can only demonstrate hypothetical estimates using mixing models. For example, a multiple-source mixing model could be used to distribute water use between groundwater and soil water before irrigation and a more robust three-end-member two-equation mixing model for separation of groundwater, soil water, and irrigation water after irrigation. To illustrate, we used a mixing model to demonstrate potential variation in the isotopic ratio of soil water using pre-irrigation isotopic ratios of deuterium in groundwater and xylem sap (Figure 5). If we assume that one-half of the xylem water originates from free soil water and apply a simple two-end-member mixing model of the form

$$f\delta D_{sw} = \delta D_{xs} - (1 - f)(\delta D_{gw})$$

where, δD_{sw} is the deuterium isotopic signature in the soil water, δD_{xs} is the signature of the xylem sap, δD_{gw} is the groundwater signature, and f represents the fraction of water taken up from the soil source. After rearranging, the formula read,

$$\delta D_{sw} = [\delta D_{xs} - (1 - f)(\delta D_{gw})]/f$$

[2]Sonya Jones, U.S. Geological Survey, Atlanta, GA.

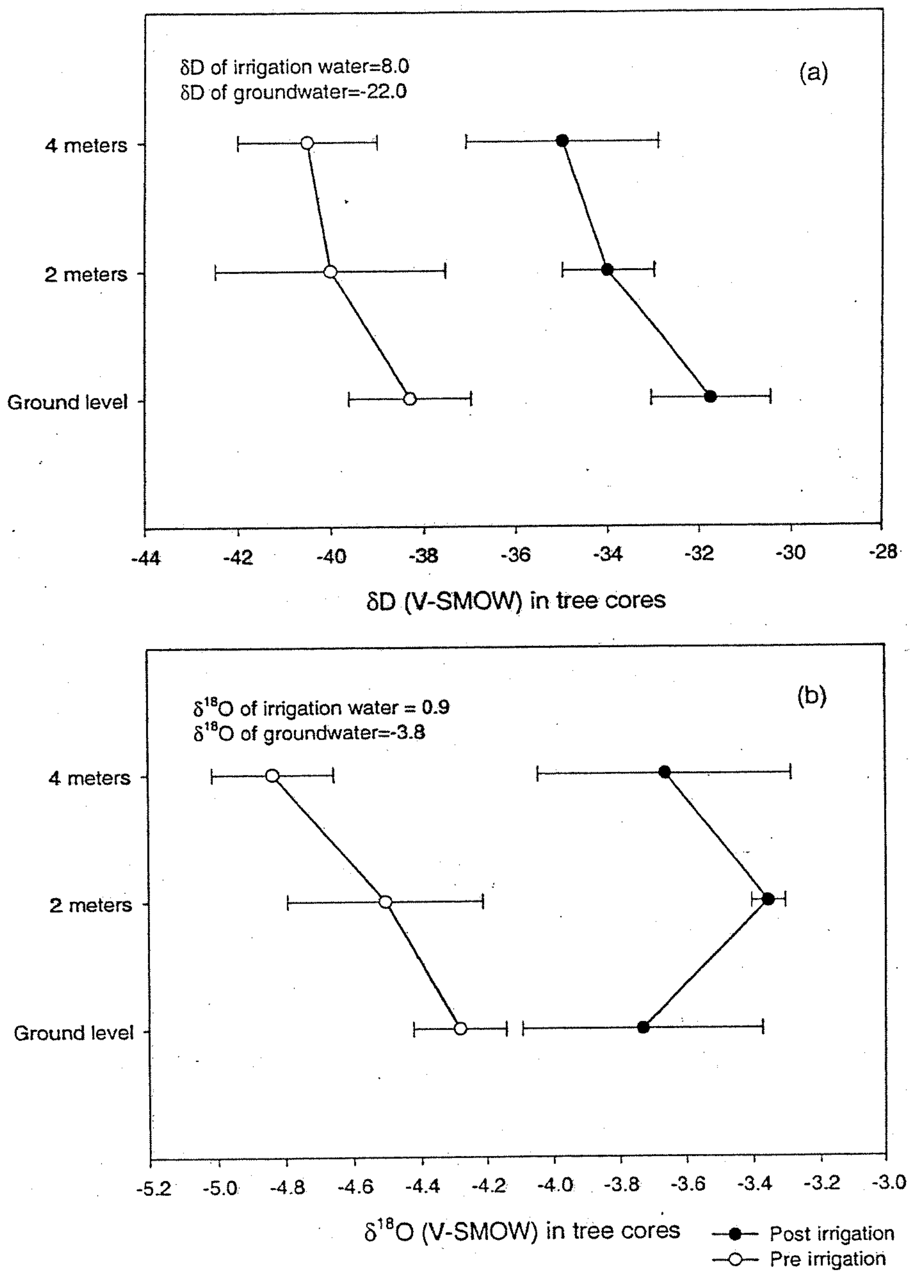

FIGURE 4. Changes in isotopic ratios (‰: Vienna–Standard Mean Ocean Water [V–SMOW]) for (a) deuterium and (b) oxygen following the irrigation treatment. Individual observations represent means across core samples and trees ($n = 2$) for each level. Error bars represent 1 standard error of the mean.

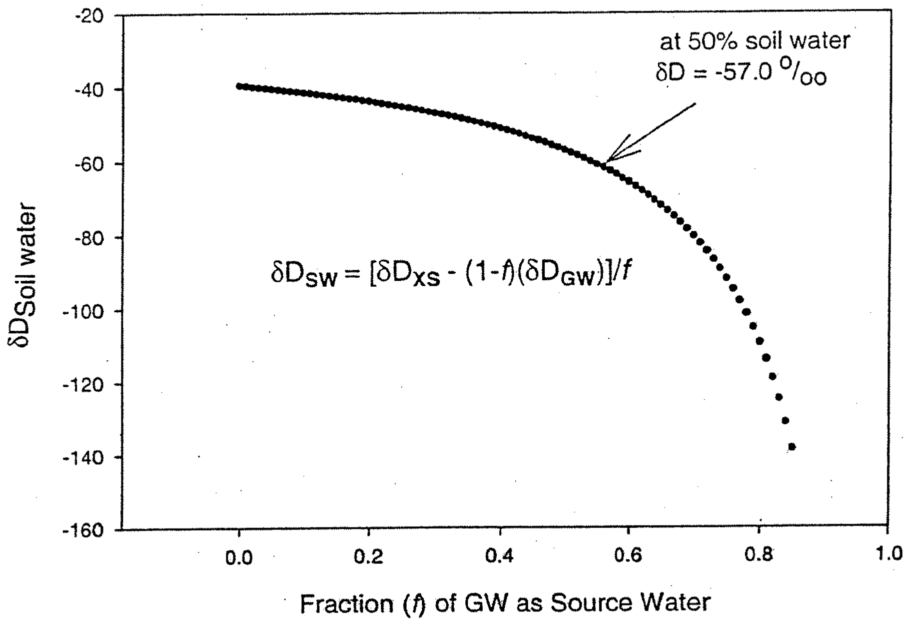

FIGURE 5. Plot of the relationship between isotopic ratios of ground water (GW), xylem sap (XS), and soil water (SW). The hypothetical value of −57% (Vienna–Standard Mean Ocean Water [V–SMOW]) was based on a 50% soil water uptake in the absence of precipitation.

making $f = 0.5$, solving for δD_{sw} yields a soil water signature of −57%. This value is slightly more enriched than meteoric water in the region and would be expected to be so due to evaporative enrichment of fallen precipitation before it completely infiltrates to lower soil horizons.

TCE Concentrations

TCE concentrations in the xylem sap averaged 977 ppb before irrigation, but uptake of nonpolluted irrigation water resulted in a dilution effect of 21% on the average and ranged from 15–34% during the study (Figure 6). Post-irrigation xylem sap TCE concentrations averaged 767 ppb. The observed dilution of TCE concentration in the xylem sap serves to illustrate a supplement by irrigation to below-ground sources during rain events. Interestingly, the magnitude of the dilution effect is disproportionately small relative to the maximum 61% sapflux increase. This suggests that although the primary source of pollution is the groundwater, TCE may be present in the soil water as well. Because we did not measure soil water TCE concentration, we can only speculate on mechanisms that could transfer TCE from groundwater to soil water. For example, there are two primary mechanisms through which TCE may become incorporated into soil water. First, groundwater levels fluctuate and during a recession may leave behind traces of TCE adsorbed to soil particles. This TCE

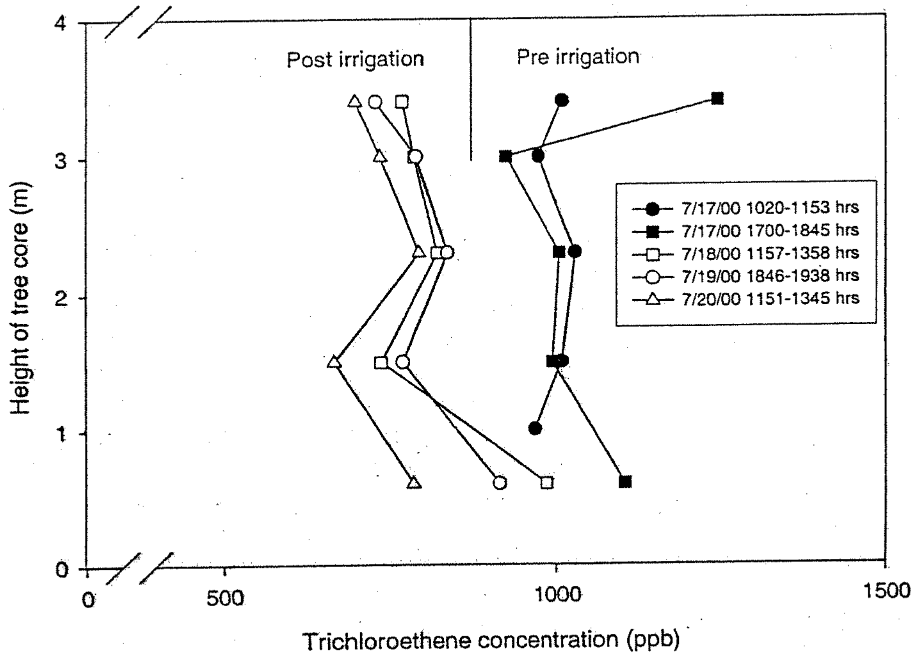

FIGURE 6. Average TCE concentrations (ppb) in headspace above tree cores before and after artificial irrigation. Individual observations represent means for each level on each day.

becomes incorporated into the soil water as plant available water percolates through the soil profile and becomes available for plant uptake. Second, "hydraulic lift" (Dawson, 1993) may transfer TCE from groundwater into the soil profile. Hydraulic lift is the nocturnal uptake of water by roots from deep soil layers (e.g., groundwater) and is subsequently released from shallow roots in the upper soil layers with no change in isotopic ratios. Dawson (1993) demonstrated the existence of hydraulic lift in sugar maple (*Acer saccharum* L.) through the use of stable isotopes and diel variation in soil water potentials. Little is known about the release of water from plant roots (Boyer, 1985), but water and carbohydrate exudates in the rhizosphere are commonly reported for plants (McCully and Canny, 1988) and there is ample evidence for soil water potentials to be more negative than plant tissue water potentials (Nobel and Sanderson, 1984) that, in the absence of a barrier of sorts, could create a strong enough gradient to cause water loss from roots. Hydraulic lift may explain the increase in total TCE flux in the xylem sap following irrigation by serving as the mechanism for movement of TCE to surface soil horizons, where TCE remains adhered to soil particles following evaporation of water from this upper soil layer. Subsequent rain events, or irrigation in this case, cause the TCE to go back in solution where it is taken up by the plant. Hence, the application of irrigation water resulted in supplementing TCE uptake from groundwater.

CONCLUSIONS AND IMPLICATIONS

Knowledge of water use patterns by species in phytoremediation applications is essential for a complete characterization of treatment effectiveness. As shown in this article, water use by *Populus deltoides* is variable depending on water availability and transpirational demand. This strategy helps ensure that species growing in dry environments can opportunistically take advantage of available water at various locations (e.g., upper soil and groundwater) and survive long-term periods of water deficit. However, studies addressing (or modeling) phytoremediation effectiveness must account for the relative proportion of surface vs. groundwater uptake. For example, if trees switch to surface water sources when soil water supply is adequate, the overall effectiveness of the phytoremediation treatment will decrease—especially in high-rainfall regions—because less pollutant is extracted from groundwater. Optimum results will depend on species, species-specific water use habits, soils and hydrologic characteristics, and the local climate regime. Finally, because we studied large and already established trees, our results are most applicable to assessments of the role of native vegetation or longer-term water use patterns of plantations. However, the potential for water uptake from groundwater and soil-water sources in *Populus deltoides* was clearly demonstrated. Additional study will be required to determine the relative proportion of groundwater vs. surface water uptake in young plantations, and how this proportion changes with stand development.

ACKNOWLEDGEMENTS

This study was supported by the Department of Defense's Environmental Security Technology Certification Program Project E95BRAB004, Gregory J. Harvey, Program Manager. We thank Drs. Jonathan Horton and Joseph Hendricks for helpful reviews of early drafts of the manuscript.

REFERENCES

Allison, G.B., Barnes, C.J., Hughes, M.W., and Leaney, F.W.J. 1984. Effect of climate and vegetation on oxygen-18 and deuterium profiles in soils. In: *Isotope Hydrology*, pp. 105–122. International Atomic Energy Agency (IAEA), Vienna Austria.

Bailey, R.G. and Hogg, H.C. 1986. A world ecoregions map for resource reporting. *Environ. Conserv.* **13**(3), 195–202.

Brady, N.C. 1974. *The Nature and Properties of Soils.* 8th ed. MacMillan, New York.

Boyer, J.S. 1985. Water transport. *Ann. Rev. Plant Physiol.* **36,** 473–516.

Dawson, T.E. 1993. Hydraulic lift and water use by plants: Implications for water balance, performance and plant-plant interactions. *Oecologia* **95,** 565–574.

Dawson, T.E. and Ehleringer, J.R. 1991. Streamside trees that do not use stream water: Evidence from hydrogen isotope ratios. *Nature* **350,** 335–337.

Eberts, S.M., Harvey, G.J., Jones, S.A., and Beckman, S.W. 2003. Multiple-process assessment for a chlorinated-solvent plume. In: *Phytoremediation: Transformation and Control of*

Contaminants, pp. 589–633 (McCutcheon, S.T. and Schnoor, J.L., Eds.). John Wiley and Sons, Hoboken, NJ.

Ehleringer, J.R. and Dawson, T.E. 1991. Water uptake by plants: Perspectives from stable isotope composition. *Plant Cell Environ.* **10,** 777–782.

Flathman, P.E. and Lanza, G.R. 1998. Phytoremediation: Current views on an emerging green technology. *J. Soil Contam.* 7(4), 415–432.

Granier, A. 1985. Une nouvelle methode pour la mesure du flux de seve brute dans le tronc des arbres. *Annales des Sciences Forestieres* **42,** 193–200.

Granier, A. 1987. Evaluation of transpiration in a Douglas-fir stand by means of sap flow measurements. *Tree Physiol.* **3,** 309–320.

Heilman, P.E., Hinckley, T.M., Roberts, D.A., and Ceulemans, R. 1996. Production physiology. In: *Biology of Populus and Its Implications for Management and Conservation*, pp. 459–489. (Stettler, R.F., Bradshaw, H.D., Jr., Heilman, P.E., and Hinckley, T.M., Eds.). NRC Research Press, Ottawa, ON, Canada.

Hinckley, T.M., Brooks, J.R., Cermak, J., Ceulemans, R., Kucera, J., Meinzer, F.C., and Roberts, D.A. 1994. Water flux in a hybrid poplar stand. *Tree Physiol.* **14,** 1005–1018.

Ingraham, N.L. 1998. Isotopic variations in precipitation. In: *Isotope Tracers in Catchment Hydrology*, pp. 87–118 (Kendall, C. and McDonnell, J.J., Eds.). Elsevier Science Publications, Amsterdam, The Netherlands.

Kozlowski, T.T., Kramer, P.J., and Pallardy, S.G. 1991. *The Physiological Ecology of Woody Plants.* Academic Press, San Diego, CA.

Martin, T.A., Brown, K.J., Cermak, J., Ceulemans, R., Kucera, J., Meinzer, F.C., Rombold, J.S., Sprugal, D.G., and Hinckley. T.M. 1997. Crown conductance and tree and stand transpiration in second-growth *Abies amabilis* forest. *Can. J. For. Res.* **27,** 797–808.

McCully, M.E. and Canny, M.J. 1988. Pathways and processes of water and nutrient movement in roots. *Plant Soil* **111,** 159–170.

Nobel, P.S. and Sanderson, J. 1984. Rectifer-like activities of roots of two desert succulents. *J. Exp. Bot.* **35,** 727–737.

Pallardy, S.G. and Kozlowski, T.T. 1981. Water relations of *Populus* clones. *Ecology* **62,** 159–169.

Stable Isotope Ratio Facility for Environmental Research. 2001. Stable isotope methods. University of Utah, Salt Lake City.

USDA Soil Survey. 1981. Soil survey of Tarrant County, Texas. USDA Soil Conservation Service Report.

Vose, J.M., Harvey, G.J., Elliott, K.J., and Clinton, B.D. 2003. Measuring and modeling tree and stand level transpiration. In: *Phytoremediation: Transformation and Control of Contaminants*, pp. 245–264 (McCutcheon, S.T. and Schnoor, J.L., Eds.). John Wiley and Sons, Hoboken, NJ.

Vose, J.M., Swank, W.T., Harvey, G.J., Clinton, B.D., and Sobek, C. 2000. Leaf water relations and sapflow in eastern cottonwood (*Populus deltoides* Bartr.) trees planted for phytoremediation of a groundwater pollutant. *Int. J. Phytorem.* 2(1), 53–73.

Vroblesky, D.A., Nietch, C.T., and Morris, J.T. 1999. Chlorinated ethenes from groundwater in tree trunks. *Environ. Sci. Technol.* **33,** 510–515.

Wershaw, R.L., Friedman, I., and Heller, S.J. 1966. Hydrogen isotope fractionation of water passing through trees. In: *Advances in Organic Chemistry*, pp. 55–67G (Hobson, D. and Speers, G.C., Eds.). Pergamon Press, Oxford, UK.

White, J.W.C., Cook, E.R., Lawrence, J.R., and Broecker, W.S. 1985. The D/H ratios of sap in trees: Implications for water sources and tree ring D/H ratios. *Geochimica et Cosmochimica Acta* **49**, 237–246.